Engine Titanium Consortium

Program Summary

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Task Title: Fundamental Studies for Nickel Billets

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Students: L. Yu

Program initiation date: June 15, 1999

Objectives:

- To establish the basic ultrasonic properties of nickel-based alloy billet materials (Expected to be IN718, and one or more of Waspaloy, IN901, R95, or IN100) and relevant inclusions as an appropriate foundation for selection of ultrasonic inspection approaches.
- To manufacture and characterize flat bottom hole (FBH), synthetic inclusion, and real defect standards to provide data for determining defect detectability and developing improved inspections.
- To improve the understanding of the relationship of defect size, shape, and composition on defect detectability in Ni alloys.

Research Activities:

- Alloy selection included IN718 and Waspaloy, and melt related defects of interest for the selected alloys. Samples were fabricated from several billets to provide properties for multiple fabrication practices and alloy types. A range of noise properties were evaluated.
- Ultrasonic property measurements include velocity, attenuation and backscatter noise.
- Synthetic inclusion standards: synthetic inclusions are being designed and fabricated for representative defect types.
- Defect characterization: natural defects will be characterized to improve understanding and provide guidance to the synthetic fabrication process

Anticipated Results:

- Improved understanding of fundamental inspection properties of Ni alloys/defects for use in inspection design and POD assessment

Accomplishments:

- Samples have been fabricated and measurements are underway for the following:
    - GFMA: From a high-noise site of a 10î-diameter IN718 GFM-forged billet.
    - VdieA: From a high-noise site of a 10î-diameter IN718 V-die-forged billet.
    - VdieB: From a low-noise site of a 10î-diameter IN718 V-die-forged billet.

- WaspA: From a high-noise site of a 10î-diameter Waspaloy billet.

- Relationship between attenuation and noise properties found to be different for nickel than for titanium. Noise increases with attenuation in Ni alloys and decreases with attenuation in Ti. Expect increases in noise with attenuation for specimens with equiaxed grains: as the mean grain size increases, the attenuation and noise FOM both increase. Ti billet specimens showed direction of maximum back-wall attenuation is usually the direction of minimum grain noise. Different trends related to recrystallization during the billet formation process:
  - Ni alloys: significant amount of recrystallization leading to equiaxed grains
  - Ti alloys: very little or no recrystallization occurs leading to large-scale macrograins elongated in the axial direction leading to inverse correlation between noise FOM and attenuation
- Process developed for fabrication of synthetic defect samples. Initial sample fabrication underway.
- Characterization of natural defects underway.

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Program initiation date: June 15, 1999

Objectives:

- To apply technology developed in Phase I for titanium billet inspection to improve nickel billet inspection.
- To perform factory inspection of approximately 100,000 pounds of nickel alloy billet, primarily INCO718, to #1 FBH sensitivity using a multizone inspection system with digital acquisition to provide necessary field experience that facilitates implementation decisions.
- To determine applicability of multizone technique to Waspaloy.
- To provide the billet industry and OEMs with demonstration of improved sensitivity inspection using FBH standards as the metric with a goal of #1FBH sensitivity in 10î INCO718 billets and #2.5FBH sensitivity in 10î Waspaloy billet.
- To provide necessary data to the Inspection Systems Capability team for estimation of POD for nickel billet, including cut-up data generated in the pilot lot inspection.

Research Activities:

- Baseline assessment: assess inspection sensitivity for conventional transducers and existing multizone transducers originally designed for inspection of titanium billet. Requires fabrication of calibration standards for use in the assessment.
- Lab demo: complete inspection development and demo on IN718 and Waspaloy calibration standards.
- Factory demo: pilot lot inspection of 100,000 lbs followed by destructive analysis of finds. Data will be collected for POD. Industry demo will be provided to supplier base.
- Small diameter assessment: lab evaluation on Ni billet 8î diameter

Anticipated Results:

- Reduction in occurrence of melt-related defects in Ni forgings through higher sensitivity inspection of Ni billets and therefore lower overall risk.

Accomplishments:

- Calibration standards completed for IN718 and Waspaloy.

- Transducer characterization methods developed for bicylindrically focused transducers. Software delivered to OEMs for internal use in transducer evaluation. Method for use by transducer vendors under development.
- Completed lab evaluation and industry demonstration of Mulitzone inspection of 10î diameter billet using transducers previously designed for titanium billet. The program goal was exceed for both alloys:
  - ï Exceed program goal of #1FBH for IN718 by 2 to 4x
  - ï Exceed program goal of #2.5FBH for Waspaloy by 2 to 11x
- Factory evaluation initiated in August 2002. The evaluation will include 75,000 lbs of IN718 and 25,000 lbs of Waspaloy.

Task Title: Inspection Development for Titanium Billet

Investigation Team: HW: Andy Kinney, Waled Hassan; **ISU:** Bruce Thompson, Ron Roberts, Frank Margetan; **GE:** Thadd Patton, Dave Copley, Wei Li, Mike Keller, Jon Bartos, Richard Klaassen, John Halase; **PW:** Kevin Smith, Jeff Umbach, Bob Goodwin, Andrei Degtyar, Harpreet Wasan

Program initiation date: June 15, 1999

Objectives:

- To provide a procedure to account for attenuation effects such that the variation between calibration and inspection sensitivity is minimized.
- To demonstrate the ultrasonic equipment and techniques required to inspect titanium alloy billets to #1FBH sensitivity for 10î diameter and below.
- To provide an initial assessment of sensitivity at diameters greater that 10î.

Research Activities:

- Transducer design models: evaluate the accuracy of transducer models developed at ISU and transfer resulting code to OEM partners for internal transducer studies
- Lab demo: complete inspection development and demo on 10î dia. billet using fixed focus transducers. Calibration standards developed in ETC Phase I will be used for the evaluations.
- Factory demo: pilot lot inspection of five heats of Ti-6-4 followed by destructive analysis of finds. Data will be collected for POD and an industry demo will be provided to supplier base.
- Assessment of large dia. billet: assess sensitivity at >10î billet and determine need for further development
- Small diameter assessment: lab evaluation on Ti billet 8î dia
- Attenuation compensation procedure: develop improved practices using results from Phase I program

Anticipated Results:

- Reduction in occurrence of melt-related defects in Ti forgings through higher sensitivity inspection of Ti billets and therefore lower overall risk

Accomplishments:

- Accuracy of transducer design models has been verified and software is being utilized by the ETC to optimize design of billet transducers.
- Transducers have been designed to arrive at improved sensitivity inspection with the objective of #1FBH sensitivity through out the 10î diameter billet. Initial transducers did

not meet design specifications. Available phased array transducers at HW and ISU are being used to experimentally evaluate the focal properties necessary to arrive at the required sensitivity. Discussion is underway as to the ability of fixed focus transducers to meet the requirements.

- Experimental studies have been completed that relate the backwall amplitude to flat bottom hole response in titanium billet. Based on these findings, a ìstraw manî for improved attenuation-compensation procedure for billet inspections has been developed which will uses the extreme BW amplitudes, rather than average BW amplitudes. Measurements for directly testing the straw man procedure have been defined and are underway. Upon completion of the procedure, it will be communicated to billet suppliers for comment before eventual implementation.

- Chord block sample was fabricated for assessment of 14î diameter billet. The sample was evaluated using available Multizone transducers and a new transducer design completed. Delivery of the new transducer is expected for evaluation in the fall of 2002.

Task Title: Fundamental Property Measurements for Titanium Forgings

Investigation Team: HW: Waled Hassan; **ISU:** Bruce Thompson, Frank Margetan, Ron Roberts, Tim Gray; **GE:** Ed Nieters, Mike Gigliotti, Lee Perocchi, Dave Copley, Wei Li, Jon Bartos, Bill Leach; **PW**: Jeff Umbach, Bob Goodwin, Andrei Degtyar, Harpreet Wasan

Students: A. Li

Program initiation date: June 15, 1999

Objectives:

- To gain the fundamental understanding of the ultrasonic properties of titanium forgings that is needed to provide a foundation for the development of reliable inspection methods that provide uniformly high sensitivity throughout the forging envelope.
- To acquire the data necessary to relate the detectability of defects in forgings to component properties (flow line characteristics, surface curvature) and defect properties (size, shape, composition, location, and orientation) thereby providing a foundation for the design of improved inspections and the evaluation of inspection capability.

Research Activities:

- Sample fabrication: forging samples with varying flow line characteristics and surface curvatures to generate POD and inspection development data for typical range of forging characteristics.
- Ultrasonic property measurements: velocity, attenuation, and backscattered noise measurements will be made as a function of forging parameters and forging geometry
- Effects of surface curvature: curvature corrections will be developed and transducer designs optimized for forging inspection in cooperation with the inspection development task

Anticipated Results:

- Complex Ti microstructure typically can significantly modify signal strength from flaws and produce competing, backscattered noise signals which interfere with detection of flaws. Understanding of UT wave propagation in Ti forgings is needed to guide development and application of inspection systems with highest possible sensitivity, to develop algorithms to most accurately interpret data, and to provide basis for evaluating capability, e.g., in determination of POD.

Accomplishments:

- Three forging geometries, one per OEM, were identified and bulk ultrasonic scans completed. Based on analysis of UT scans, property blocks were sectioned to provide a range of microstructural and forging flow line properties.

- Property measurements for the 24 coupons have been completed and correlation to microstructural and forging properties is underway.
- Six samples with various concave and convex curvatures have been fabricated. Investigations of the manner in which surface curvature influences inspection sensitivity in forgings are underway. This will include testing of models that predict the characteristics of backscattered grain noise seen during forging inspections. After successful validation, the models can be applied to other surface curvatures to arrive at the optimal inspection parameters.
- Design of a synthetic inclusion disk has been completed and fabrication methods have been determined.

Task Title: Inspection Development for Titanium Forgings

Investigation Team: HW: Andy Kinney, Waled Hassan; **ISU:** Tim Gray, Bruce Thompson, Frank Margetan, Ron Roberts**; GE:** Thadd Patton, Dave Copley, Ed Nieters, Wei Li, Bob Gilmore, , Jon Bartos, , Richard Klaassen, Mike Keller, John Halase; **PW:** Jeff Umbach, Bob Goodwin, Andrei Degtyar, Harpreet Wasan, Dave Raulerson, Kevin Smith

Program initiation date: June 15, 1999

Objectives:

- To develop a high sensitivity ultrasonic inspection of titanium forgings utilizing a 1/128î (#) FBH calibration target, digital C-scan image acquisition, and signal-to-noise rejection criteria target without significant cost increase.
- To demonstrate the new technique in a production environment over an extended period to determine its feasibility (both cost and readiness) as a production inspection.

Research Activities:

- Forging selection: one forging will be selected from each OEM for use through out the program. Scan plans will be generated to arrive at # FBH sensitivity through out the forging geometry.
- Transducer design and selection: model based approaches will be taken to optimize transducer design. Software will be transitioned to OEMs for use in internal studies.
- Surface finish effects: determine effect of surface finish on inspectability. This is viewed as a critical issue in meeting the aggressive sensitivity goals of this program.
- Laboratory demonstration: maximum productivity approach will be assessed in the lab demo. Testbeds will be established for both fixed-focus and phased array inspection setups as part of the inspection development.
- Factory testbed: optimal system will be transitioned to factory environment including evaluation of 30 forgings and will include factory demo for the forging suppliers.

Anticipated Results:

- Typical forging inspection practices include use of 10MHz focused transducers with focal properties chosen to provide adequate sensitivity in the #1FBH to #2FBH range and may include the use of several zones. Phase I focused on inspection of Ti billet, particularly Ti-6-4, and detection of hard alpha. Extensive fundamental understanding was developed for inspection properties of billet and to a limited extent of Ti forgings. More extensive treatment is needed to address effects of anisotropy and surface curvature on inspection of titanium forgings. With that understanding, a reduction in the number of melt related defects introduced into service will result, thereby reducing the overall fleet risk. Data will be collected for use in POD estimates.

Accomplishments:

- A forging geometry has been selected by each of the OEMs for use in the evaluation. The same geometry used for the fundamental studies are being used in the inspection development.
- Calibration blocks have been designed and fabricated. The blocks will cover the range of thicknesses present in the three forgings selected by the OEMs.
- Surface finish can have detrimental effect on inspection sensitivity and a quantitative understanding of the effect is needed. An experimental plan has been developed and sample fabrication initiated. Data will be analyzed by the team to relate surface finish conditions to near surface resolution and to signal to noise ratio. Relationship to be established between feed rate and front surface signal ringdown. This work has implications for surface finish allowables.
- Beam properties necessary to achieve # FBH sensitivity have been determined through a combination of theoretical and experimental studies. Determined that a total of nine zones accomplished with three transducers focused at three depths each would be needed for inspection of the three forgings. Transducers have been ordered for the lab evaluation and eventual factory inspections.
- A limited evaluation of phased array inspection for forging geometries is planned as part of the program. ISU facilities will serve a testbed for the team in evaluation and development of phased array approaches. Design of a 128-element phased array has been completed and the order placed for the transducer.

Task Title: High Speed Bolthole Eddy Current Scanning

Investigation Team: HW: Jim Ohm, Andy Kinney, Waled Hassan; **ISU:** Lisa Brasche; **GE:** Tony Mellors; **PW:** Kevin Smith, Dave Bryson, Rob Stephan

Program initiation date: June 15, 1999

Objectives:

- To develop common fixtures to reduce inspection variables and arrive at a standardized inspection technique.
- To measure the process capability.
- To utilize this information to develop an industry best practice document.

Research Activities:

- Evaluation of existing processes: comparison of current OEM practices will be completed.
- Development of common tooling: emphasis will be placed on variability reduction and defect detectability improvements.
- Development of common process: common inspection technique will be developed and published as an SAE AS4787.

Anticipated Results:

- High Speed Bolt Hole (HSBH) eddy current inspection has emerged as the leading inspection technique for fast and accurate inspection of circular bolt and air holes. Compared to automated system bolt hole inspections, the HSBH inspection is a simple, low cost technique that can offer comparable sensitivity to cracks. HSBH also provides a more sensitive inspection than FPI, particularly for inspection of long/deep holes often found in critical rotating components. Recent incidents have identified the need for more sensitive inspections and led to the introduction of eddy current HSBH techniques in the field. Emphasis on this technique is expected to increase as industry continues to pursue inspection of critical features for cracks as a result of service induced fatigue, abusive machining, or other hole damage. Differences among OEM techniques are unknown and quantification of inspection capability is not available. The industry will benefit from a common, improved inspection technique that reduces inspection variability and standardizes the inspection process.

Accomplishments:

- Surveyed OEMs to define existing techniques: Baseline practices for HSBH EC found to be similar among OEMs. Common OEM practice is primarily a manual inspection with hand feed and occasional use of a simple staging device to assist in maintaining probe alignment and normality with the surface of the hole. Procedural guidelines are currently used to control the maximum feed rate for use in a particular scan with reliance on the operator in assuring compliance. Probe type and size show widespread use of reflection differential type probes with increasingly smaller nominal coil diameters in the range of 0.040î to 0.060î. Review of vendor equipment showed OEM practices consistent with the range of available bolthole scanners, instruments and probes.

- Conducted DOE to evaluate critical parameters of the HSBH technique: The DOE was a three factor full factorial design (i.e., 8 combinations) blocked for motor speed and randomized within each block. Fatigue cracks ranging from 7 to 60 mils were used in the study. Factors/Levels were as follows:

Probe RPM	1200 / 2200
Probe Feed	0.125î/sec / 0.750î/sec
Probe Angle	0 degrees / 2 degrees

- Results were analyzed and reported. All three factors were found to have an effect with probe angle being most important.
- Tooling concepts have been considered and a first prototype design for common fixturing completed. Design concepts have been finalized and arrangements are underway for fabrication.

Task Title: Engineering Studies of Cleaning and Drying Process in Preparation for FPI

Investigation Team: HW: Andy Kinney; **ISU:** Brian Larson, Rick Lopez, Lisa Brasche; **GE:** Terry Kessler; **PW:** Anne D'Orvilliers, Kevin Smith, Jeff Stevens, John Lively; **RR**: Bill Griffiths, Keith Griffiths, Pramod Khandewal; **Delta:** Lee Clements, Scott Vandiver

Students: L. Rohberg, S. Gorman

Program initiation date: February 15, 2000

Objectives:

- Determine the effect of chemical cleaning, mechanical cleaning, and drying processes on the detectability of low cycle fatigue cracks in titanium and nickel alloys
- Establish a quantifiable measure of cleanliness, including the minimum condition to allow effective inspection processing
- Establish the effect of local etching on detectability and provide guidance on best practices for removal of local surface damage from FOD and other surface anomalies
- Update existing specifications to reflect the improved processes and provide best practices documents for use by the OEMís and airlines

Research Activities:

- Survey of current practices (airlines & OEMs)
- Sample fabrication (lcf cracks in Ti and Ni)
- Develop quantitative characterization measurements (similar to AFML QPL process)
- Baseline samples at ISU
- Establish matrix of contaminants and cleaning methods and determine drying study parameters
- Perform comparison studies at Delta using industry inspection facility
- Analyze results, prepare final report, and share findings with industry groups for consideration in specification changes

Anticipated Results:

- Fluorescent penetrant inspection, the most widely used NDT method, is commonly employed for both production and inservice inspection of engine and airframe components. It is often the only NDT method used for ensuring flight safety of critical rotating components. It is therefore recognized by ETC, other OEMs, airlines, and FAA that significant efforts should occur to improve the overall reliability of the penetrant process. One of the most critical steps in the penetrant process is that of pre-penetrant surface preparation which is being addressed in this program.

Accomplishments:

- Over eighty samples containing low cycle fatigue cracks were fabricated at ISU. Samples were characterized using optically microscopy and baseline brightness measurements using photometer techniques similar to those in use by the USAF.
- Baseline characterization of the samples were completed at ISU prior to field studies at Delta.
- Three separate, one-week visits were made to Delta Airlines in Atlanta Ga. The first study was completed in June 2001 and compared flash dry and oven dry methods. The other two visits were made to assess eight chemical cleaning and six mechanical cleaning methods and occurred in October 2001 and February 2002.
- Contaminants evaluated during the cleaning studies included oils, service coatings (RTV, antigallant compound, and high temperature sealant), and baked on contamination (oxidation/scale, soot, and coke/varnish.)
- The final report has been submitted to the FAA for review and is expected for publication in fall 2002.